

GLOSSARY

21 centimetre radiation Electromagnetic radiation with a wavelength of 21 cm, in the radio part of the spectrum, which is emitted or absorbed by a hydrogen atom when it undergoes a spin–flip transition. The spin–flip transition of a hydrogen atom may be described in term of classical (i.e. non-quantum) physics by saying that the proton and electron which comprise the atom change from having their spins aligned parallel with one another to being antiparallel (180° out of alignment), or vice versa.

Abell radius The typical radius of a cluster of galaxies. It is now known to be about 2 Mpc.

absolute visual magnitude An intrinsic property of a star, equal to the apparent visual magnitude the star would have if observed from a standard distance of 10 parsecs, in the absence of interstellar absorption. The absolute visual magnitude provides a measure of the star's luminosity.

accelerating model A cosmological model, belonging to the class of Friedmann–Robertson–Walker models, in which the rate of change of the scale factor is itself changing at a positive rate (i.e. $\ddot{R} > 0$). Although any FRW model with a sufficiently large cosmological constant Λ may exhibit accelerated expansion at late times in its development, the term ‘accelerating model’ is often used to refer specifically to the model with positive cosmological constant ($\Lambda > 0$) and zero curvature parameter ($k = 0$).

accretion disc A disc of gas and dust which forms around a massive object such as the accreting star in an interacting binary system, or around the massive black hole in the engine of an AGN. Material spirals inwards within the disc and falls onto the central object from the inner edge of the disc.

acoustic peaks A set of peaks, the largest of which is called the Doppler peak, seen in the angular power spectrum of the cosmic background radiation for multipole numbers in the range from about $l = 50$ to $l = 1000$ (i.e. on angular scales between about 0.1 degrees and a few degrees). The phenomenon is partly due to the localized heating of the last-scattering surface caused by the acoustic waves in the photon–baryon fluid that is present there, and partly due to the effect that the moving charged particles, associated with those waves, have on the wavelengths of scattered photons.

acoustic waves Waves in a fluid arising from the tendency of localized concentrations of pressure or density to return to some preferred equilibrium value by increasing the pressure or density in neighbouring regions. Acoustic waves are also known as sound waves.

active galactic nucleus (AGN) The bright, point-like object at the centre of an active galaxy. AGNs typically have high luminosities and often exhibit rapid variability.

active galaxy A galaxy that typically exhibits an unusually high and varying luminosity, and which may additionally show signs of energetic processes connected with its central regions. The term embraces: Seyfert galaxies, quasars, radio galaxies and blazars.

age–metallicity relation The tendency for older stars to have lower metallicities.

AGN *See* active galactic nucleus.

angular power The quantity, usually denoted as $l(l+1)C_l/2\pi$ and measured in units of $(\mu\text{K})^2$, that is plotted on the vertical axis of an angular power spectrum, and which measures the amount of variation present in the corresponding (anisotropy) map on the angular scale $\theta = 180^\circ/l$.

angular power spectrum A mathematical entity, often presented as a plot of angular power against multipole number, that is used to describe the statistically important data contained in a two-dimensional map of temperature anisotropies in the cosmic microwave background.

anisotropies (in the cosmic microwave background) Variations in the intensity of the cosmic microwave background radiation over the celestial sphere.

annihilation The interaction between a particle and its corresponding antiparticle in which both the particle and antiparticle are destroyed and energy is released. This is the opposite process to pair-creation.

anthropic principle An assertion that the existence of intelligent life in the Universe is of cosmological significance. In its weak form, the anthropic principle states that conditions in the Universe are those which allowed the emergence of intelligent life. In its strong form, the principle states that the Universe necessarily had conditions that led to the emergence of intelligent life.

antibaryon An elementary particle that comprises three antiquarks. An example of an antibaryon is the antiproton.

apparent surface brightness The quantity that describes the apparent brightness at any point on an extended object, such as a galaxy. The apparent surface brightness at any chosen point is the amount of radiant flux that would reach 1 m^2 at Earth from a small, uniformly bright, square region, of angular area $1 (\text{arcsec})^2$, surrounding the chosen point. An acceptable SI unit of apparent surface brightness is the $\text{W m}^{-2} \text{arcsec}^{-2}$.

apparent visual magnitude A quantity that describes the apparent brightness of a body. For a star, it is a measure of the flux density received in the V band, i.e. a band that approximates the response of human vision versus wavelength.

atomic hydrogen Hydrogen in the electrically neutral state in which it contains a single proton bound to a single electron. This form may be distinguished from other common forms of hydrogen such as molecular hydrogen and ionized hydrogen.

band-shifting The effect whereby electromagnetic radiation from a highly red-shifted object will be observed in a different wavelength band to that in which it was emitted.

bar instability The process by which a system of stars orbiting their common centre of gravity in a flattened (disc-like) configuration, tends to develop an elongated (bar-shaped) rather than circular distribution.

barred galaxy Any spiral, lenticular or irregular galaxy with a central bar-like feature.

barred spiral galaxy Any spiral galaxy whose central stars form an elongated (bar shaped) distribution, with the long axis lying in the plane of the disc.

baryon An elementary particle that comprises three quarks. Protons and neutrons are examples of particles that are baryons.

baryon number A quantity that is conserved in all particle interactions (with the exception of some speculative interactions predicted by grand unified theories). The baryon number of any baryon is $+1$ and that of any antibaryon is -1 respectively (or equivalently, the baryon number of any quark is $+1/3$, whereas that of any antiquark is $-1/3$). The baryon number of any other particle is zero.

baryonic dark matter Dark matter consisting of baryons that do not produce any detectable radiation. It is generally believed that most dark matter is non-baryonic.

big bang The early part of the expansion of the Universe, as described by those Friedmann–Robertson–Walker models that start with the scale factor R equal to zero at time $t = 0$ and with the rate of change of the scale factor being positive ($\dot{R} > 0$).

big crunch The late part of the contraction of the Universe, as described by those Friedmann–Robertson–Walker models that end with the scale factor R equal to zero and with the rate of change of the scale factor being negative ($\dot{R} < 0$).

BL Lac object (BL Lacertae object) A subclass of blazar. In contrast to optically violent variables, the spectra of BL Lac objects show no emission lines.

black hole A region of space from which, according to general relativity, signals (including particles of matter and electromagnetic radiation) are unable to escape due to the action of gravity. Such regions are bounded by an event horizon, and may be created by the catastrophic collapse of massive stars.

black-body spectrum The spectrum of an ideal thermal source of radiation (i.e. a black body). This is a continuous spectrum with a characteristic ‘humped’ shape, the peak wavelength depending on the temperature of the source, in accord with Wien’s displacement law. A characteristic of sources that produce spectra that are close to the black-body form is that there is a degree of interaction between electromagnetic radiation and the material that makes up the source. (This leads to the formal definition of a black-body source as one that has the property of absorbing perfectly any electromagnetic radiation that is incident on it and emits a black-body spectrum.)

blazar A kind of active galaxy, characterized by a point-like appearance, a relatively featureless optical spectrum, and rapid variability across the electromagnetic spectrum. Blazars may be subclassified as BL Lac objects or optically violent variables.

borehole survey A survey of galaxies in which a wide range of redshifts is measured over a narrow range of directions (angles). Such surveys extend out to very great distances and are generally described as ‘deep’ surveys.

bottom-up scenario See hierarchical scenario.

broadband spectrum A spectrum covering a wide range of wavelengths or frequencies, which indicates the energy distribution of a source. It does not generally show narrow features such as absorption lines.

broad-line region (BLR) The body of gas responsible for emitting the broad emission lines in an AGN. The typical width of broad emission lines corresponds to radial velocity variations of about 5000 km s^{-1} .

bulge The region around the centre of a spiral galaxy, where the galaxy is thicker and brighter and the concentration of matter is greater than elsewhere. Its outer parts are dominated by the light of old stars, but towards the centre it contains material associated with the inner parts of the disc including sites of star formation.

Butcher–Oemler effect The observation that young galaxies (i.e. those observed at very large distances) tend to have more blue stars than older galaxies (i.e. those nearby). This provides evidence for the evolution of stellar populations.

calibration problem The difficulty of establishing the relationship between various methods for measuring relative distances and of deducing absolute distances from relative distances, arising largely from difficulties in determining the luminosity of standard candles.

Casimir effect The effect whereby two parallel, uncharged, metal plates will experience a mutual attraction, of electromagnetic origin, when narrowly separated in a vacuum. The effect arises because the plates modify the physical properties of the intervening vacuum. In particular, the pressure of the vacuum between the metal plates is lower than the pressure of the surrounding vacuum, giving rise to the forces that act on the plates.

cD galaxy Any supergiant elliptical galaxy with a large diffuse envelope.

Cepheid variable method The use of a (classical) Cepheid as a standard candle for the purposes of distance determination. The method is based on the fact that for classical Cepheids the absolute magnitude is proportional to the period of brightness variation.

chaotic inflation A hypothesis which assumes that the entire Universe is partitioned into domains, and that the laws of physics may differ from one domain to another. In the chaotic inflation scenario, the physical laws that lead to inflation occur by chance in some of these domains. Such a scenario avoids the need to explain why conditions in a single Universe were ‘just right’ to produce inflation.

chimneys Regions of hot, low-density gas in the disc of the galaxy where supernova explosions have heated the local interstellar medium and caused it to break out from the disc. Such structures are believed to provide channels whereby gas from the disc can flow into the tenuous halo.

classical Cepheids A type of giant/supergiant star which pulsates regularly with a period in the range from about a day to about 100 days. The changes in radius, temperature, and hence luminosity, arise from instabilities in the envelopes of such evolved giant or supergiant stars. Classical Cepheids, which are Population I stars, can be distinguished from another category of stars with similar but nevertheless distinct properties, the Population II Cepheids.

closed model A cosmological model, belonging to the class of Friedmann–Robertson–Walker models, that starts with a big bang and ends with a big crunch. The closed model is characterized by zero cosmological constant ($\Lambda = 0$) and a positive curvature parameter ($k = +1$). In such a model the cosmic density is always greater than the critical density.

cluster (of galaxies) A concentration of galaxies in a region of space, of order 4 Mpc across.

cold dark matter (CDM) Dark matter that is comprised of particles whose speeds are low in comparison to the speed of light.

collisional excitation The process in which an ion, atom or molecule is raised to a higher energy state as a result of its collision with another particle.

colour index The quantity that describes the colour of a star, obtained by subtracting its apparent magnitude in one wavelength band (e.g. its apparent visual magnitude) from its apparent visual magnitude in a different band (e.g. in blue light). In this example, the colour index would be denoted $B - V$. The colour index of a star depends primarily on its temperature.

co-moving A term used to indicate a state of expansion or contraction matched to that of the Universe as a whole. The term is typically applied to ‘co-moving coordinates’ which allow points moving with the Hubble flow to be described by fixed coordinate values despite their increasing physical separation.

co-moving volume Any volume of space whose boundary is fixed in co-moving coordinates.

confidence level A numerical quantity, usually expressed as a percentage, describing the likelihood that the true value of a measured quantity lies within some specified range of values.

Copernican principle The principle that the Earth does not occupy a privileged position in the Universe.

co-rotation radius The distance, measured from the centre of a spiral galaxy, at which the orbital speed of the stars about the galaxy and the pattern speed of the spiral arms is the same.

cosmic background radiation The electromagnetic radiation that pervades the Universe. At the present time, the peak of the spectral energy distribution of the cosmic background radiation occurs at microwave wavelengths and is observed as the cosmic microwave background.

cosmic microwave background (CMB) The contribution to the observed astronomical ‘background radiation’ that has no identifiable stellar or galactic source and which occupies the wavelength range from about 0.1 mm to 0.1 m. The cosmic microwave background is of great importance in modern cosmology and is often represented by the abbreviation CMB. In terms of total energy content, the CMB represents the dominant form of radiation in the Universe. It is characterized by a black-body spectrum corresponding to a temperature of (2.725 ± 0.002) K, and has a highly isotropic distribution with intrinsic temperature anisotropies of no more than a few parts in 10^5 .

cosmic recycling The cycling of gas through various forms in the Galaxy, from the interstellar medium into stars and then back into the interstellar medium (towards the end of the star’s life). In this process the metallicity of the gas is increased by the production of heavier elements in stars.

cosmic shear The effect whereby distant galaxies appear to be distorted and displaced due to the gravitational deflection of the light from those galaxies as it encounters non-uniformities in the large-scale distribution of matter. An analysis of the consequences of cosmic shear provides a way of mapping the distribution of matter in the Universe.

cosmic variance A source of uncertainty in the determination of the angular power spectrum of the cosmic microwave background, arising from the fact that the temperature anisotropies on which the determination is based are being measured from just one location in the Universe (i.e. the spectrum of a cosmic phenomenon is being estimated on the basis of a single sample of data).

cosmological constant A constant, usually denoted Λ , that appears in the Einstein field equations of general relativity, and through them plays a role in many relativistic cosmological models. A positive cosmological constant causes an effective repulsion between distantly separated points in space, and may result in an eventual acceleration in the rate of cosmic expansion. *See also* dark energy.

cosmological model A mathematical model of the Universe as a whole, usually involving equations and parameters. Typically, a cosmological model describes the large-scale geometry of space and time, the contents of space and time, and the evolution of the parameters that describe the geometry and contents of space and time. *See also* Friedmann–Robertson–Walker models.

cosmological principle The principle (essentially an assumption based on increasingly good observational evidence) that on sufficiently large size scales, the Universe is homogeneous and isotropic. In this context, the phrase ‘sufficiently large size scales’ is usually taken to mean a few hundred megaparsecs or more.

cosmological redshift The contribution to the redshift (i.e. the fractional increase in wavelength $z = (\lambda_{\text{obs}} - \lambda_{\text{em}})/\lambda_{\text{em}}$) of radiation emitted from a distant source which arises from the large-scale expansion of the Universe. Note that the observed redshift of a distant galaxy is usually the sum of a cosmological redshift and another contribution arising from the peculiar motion of the galaxy relative to the large-scale expansion.

cosmology The branch of science concerned with the Universe as a whole, including its origin, structure, composition, evolution and eventual fate.

counts-in-cells (method) A method of characterizing the non uniformities in a distribution (such as the distribution of galaxies on the sky) based on the relative variation in density of the distribution when it is divided into cells of a given size, and the way that relative variation in density changes as the cell size is altered.

critical density The value of the cosmic density, $\rho_{\text{crit}}(t) = 3[H(t)]^2/(8\pi G)$, that would cause a Friedmann–Robertson–Walker model with Hubble parameter $H(t)$ at time t and zero cosmological constant ($\Lambda = 0$) to be a critical model. The critical density provides a useful reference value in discussions of the cosmic density and is used in defining the density parameter for matter and the density parameter for the cosmological constant. (In a FRW model where $H(t_0) = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$ at some time t_0 , the critical density at that time is $\rho_{\text{crit}}(t_0) \approx 1 \times 10^{-26} \text{ kg m}^{-3}$.)

critical model A cosmological model, belonging to the class of Friedmann–Robertson–Walker models, that starts with a big bang and expands continuously but in such a way that the rate of change of the scale factor approaches zero as the time t approaches infinity. The critical model is characterized by zero cosmological constant ($\Lambda = 0$) and zero curvature parameter ($k = 0$). In such a model the cosmic density is always equal to the critical density. The critical model is also referred to as the Einstein–de Sitter model.

curvature A geometric property of space, or of space–time, that may be used to describe departures from ‘flat’ geometry.

curvature parameter A parameter (i.e. a quantity that may vary from case to case, but which takes a constant value in any given case) that appears in the Robertson–Walker metric, and which helps to characterize the curvature of space or space–time, and which may take the value +1, 0, or –1.

damped Lyman α system A relatively dense cloud of un-ionized gas that is detectable from the very strong Lyman α absorption that it causes in the spectrum of a background quasar. It is speculated that such clouds may be galaxies that are in the process of forming.

dark energy The energy, whatever its nature, that may be associated with an effective cosmological constant Λ via the relation $\rho_\Lambda = \Lambda c^2/(8\pi G)$, where $\rho_\Lambda c^2$ represents the (uniform) energy density of the dark energy.

dark matter Matter that can be detected through its gravitational attraction, but which appears neither to emit nor absorb electromagnetic radiation, and hence gives few clues as to its nature. Some fraction of the dark matter is made up of baryons (baryonic dark matter), but most is believed to be composed of something else (non-baryonic dark matter).

dark-matter halo An approximately spherical volume surrounding the luminous parts of a galaxy where a large quantity of dark matter resides. The luminous parts of galaxies probably occupy the highest density part of the dark-matter halo and are held in place by the gravity of the dark matter.

de Sitter model A cosmological model describing a universe in which there is a negligible amount of matter and the cosmological constant Λ is positive. In the de Sitter model, space is infinite and in a state of perpetual expansion, as described by the scale factor $R \propto e^{Ht}$, where $H = (\Lambda c^2/3)^{1/2}$. The de Sitter model is a limiting case of the Friedmann–Robertson–Walker model with $k = 0$ and $\Lambda > 0$.

deceleration parameter The time-dependent quantity $q(t) = R\ddot{R}/[\dot{R}]^2$ that arises in any Friedmann–Robertson–Walker model in which the scale factor at time t is $R(t)$, its rate of change at the time t is $\dot{R}(t)$ and the rate of change of $\dot{R}(t)$ at that time is $\ddot{R}(t)$. To the extent that such a model describes the real Universe, the current value of the deceleration parameter $q(t_0)$ should equal the quantity q_0 that quantifies departures from Hubble’s law in the formula $H_0 d = cz[1 + (1 - q_0)z/2]$.

deep survey An astronomical survey that is performed with sufficient sensitivity to detect very faint sources. Typically, deep surveys require long observation times and are consequently restricted to small areas of the sky.

dense cloud One of the coldest and densest kinds of cloud to be found in the interstellar medium, usually rich in molecules. Dense clouds give birth to stars, mainly in the form of open clusters.

density fluctuations Variations in the average density, on a given size scale, within a density distribution, such as that of matter in the early Universe.

density parameter for matter The time-dependent quantity $\Omega_m(t) = \rho(t)/\rho_{\text{crit}}(t)$ that arises in any Friedmann–Robertson–Walker model where the density of matter at time t is $\rho(t)$ and the critical density at that time is $\rho_{\text{crit}}(t) = 3[H(t)]^2/(8\pi G)$.

density parameter for the cosmological constant The time-dependent quantity $\Omega_\Lambda(t) = \rho_\Lambda/\rho_{\text{crit}}(t)$, that arises in any Friedmann–Robertson–Walker model where $\rho_\Lambda = \Lambda c^2/(8\pi G)$ is the ‘density’ associated with the cosmological constant Λ and $\rho_{\text{crit}}(t) = 3[H(t)]^2/(8\pi G)$ is the critical density at time t . Note that $\rho_\Lambda c^2$ is sometimes referred to as the density of dark energy and that $\Omega_\Lambda(t)$ may accordingly be referred to as the density parameter for dark energy.

density wave theory An explanation of the formation and maintenance of the density enhancements thought to be responsible for spiral arms. The density wave sweeps around the galaxy, compressing the material it traverses and triggering star formation.

deuteron A nucleus of deuterium. It comprises one proton and one neutron.

differential rotation A pattern of rotation in which the rotation period of one part of the rotating system may differ from that of another. In the case of the Milky Way, for example, the rotation period of different parts of the disc varies with their distance from the centre. *See* rotation curve.

dipole anisotropy The large-scale variation in the intensity of the cosmic microwave background due to the Earth's motion with respect to the Hubble flow.

disc A major structural component of spiral galaxies, containing most of the visible matter of the galaxy in a highly flattened distribution.

distance ladder A synthesis of techniques for measuring astronomical distances. The distance ladder is based on using one method of distance determination to calibrate another method that is appropriate to measurements of larger distances – which can then be used to calibrate a method that is used over yet larger distances and so on.

Doppler broadening The effect whereby the width of a spectral line is increased as a result of movements within the region where the line originates. *See* Doppler effect; Doppler shift.

Doppler effect The effect whereby the observed frequency of waves received from a source depends on the motion of the source relative to the observer. There is a corresponding change in the observed wavelength.

Doppler shift The difference, arising from the relative motion of an observer and a source of radiation, between the observed wavelength (or frequency) of the radiation and the wavelength (or frequency) of that radiation at its point of emission.

dust Small solid particles, around 10^{-7} or 10^{-6} m across, found mixed with interstellar gas. Dust grains are predominantly composed of graphite and silicates, but may be surrounded by an icy mantle. Dust is very effective at absorbing and scattering ultraviolet and visible light.

dwarf elliptical Any small, intrinsically faint, elliptical galaxy, typically of type E0 and with a mass of about $10^6 M_{\odot}$.

Eddington limit The limiting luminosity of an accreting body such as an accreting massive black hole which is set by the outward radiation pressure on infalling material. This limit is proportional to the mass of the accreting body.

Eddington–Lemaître model A cosmological model belonging to the class of Friedmann–Robertson–Walker models, in which the rate of change of the scale factor is positive at any positive time t (i.e. $\dot{R} > 0$ for all $t > 0$) implying perpetual expansion, but in which \dot{R} approaches zero as t approaches zero indicating a long period of quasi-static behaviour (similar to the behaviour of the Einstein model) before the expansion really takes hold. The Eddington–Lemaître model is characterized by

a positive cosmological constant ($\Lambda = 4\pi G\rho/c^2$) and a positive curvature parameter ($k = +1$).

Einstein–de Sitter model An alternative name for the critical model.

Einstein field equations The key equations of general relativity that relate the geometric properties of space–time (such as curvature) to the distribution of energy and momentum. In applying general relativity to problems in cosmology, Einstein argued for the inclusion of a term involving the cosmological constant, Λ , that was absent from his original formulation of the field equations. The significance of this modification has remained controversial since its introduction.

Einstein model A cosmological model describing a static universe in which space is finite but unbounded and ‘straight’ lines close back upon themselves. The Einstein model was the first relativistic cosmological model and is now regarded as a special case in the family of Friedmann–Robertson–Walker models characterized by a uniform distribution of matter with density ρ , a positive cosmological constant $\Lambda_E = 4\pi G\rho/c^2$ and a curvature parameter $k = +1$.

Einstein ring The circular image produced when a point source of light lies directly behind a symmetrical gravitational lens.

ekpyrotic model A speculative model for the early Universe which does not invoke the process of inflation. In the ekpyrotic model, our Universe corresponds to a sheet or ‘brane’ that moves through a higher dimensional space (the ‘bulk’). The collision of the brane on which our Universe resides, with the brane of another ‘Universe’ may give rise to the effects that are commonly attributed to inflation.

ellipsoid A three-dimensional shape whose cross-section is always elliptical. It has three principal axes.

elliptical (galaxy) Any member of the Hubble class of galaxies characterized by an overall elliptical shape and central concentration of brightness. Membership of this class is indicated by the letter E, followed by a number that denotes the flattening factor of the galaxy.

energy A property of systems (such as arrangements of particles of matter or distributions of radiation) that measures their ability to do work. According to general relativity, the distribution of energy throughout a region of space–time is one of the factors that plays a role in determining the curvature of that region of space–time. The SI unit of energy is the joule (J).

engine The power source within an AGN. It is generally believed, but not proven, that the engine is an accreting massive black hole.

epoch of reionization The stage in the evolution of the Universe at which the neutral gas that had been present since the time of recombination first became ionized, possibly due to the intensity of ultraviolet radiation from newly formed stars or AGN. It is believed that reionization occurred when the age of the Universe was less than 10% of its current value.

evaporation The process by which there is a gradual loss of stars from an open cluster due to their acquiring sufficient kinetic energy to escape. The energy to escape is provided by gravitational forces exerted by other stars.

event horizon The bounding surface of a black hole, at which the escape speed is equal to the speed of light in a vacuum. According to general relativity, the event horizon encloses a region of space from which signals (including particles of matter and electromagnetic radiation) cannot escape.

exponential function A mathematical function of the form $y = y_0 e^{ax}$, where $e \approx 2.718$, a is a parameter which may be positive or negative, and y_0 is the value of y when $x = 0$. Many natural processes can be described quantitatively by the exponential function.

Faber–Jackson relation A relationship between the luminosity and the velocity dispersion of elliptical galaxies.

field galaxy Any galaxy that is not a member of a cluster of galaxies.

finite A property of certain cosmological models (or more specifically of certain space–times) implying that the total volume of space is of limited extent.

flux density (F) A quantity describing the rate at which energy transferred by radiation is received from a source, per unit area facing the source. The SI unit of flux density is the watt per square metre (W m^{-2}).

forbidden line A spectral line that can only be produced in a very low density gas. Forbidden lines cannot normally be produced in the laboratory.

frequency The rate at which wavelengths of a wave pass a fixed point (i.e. the number per second passing the fixed point). The SI unit of frequency is the hertz (Hz), where $1 \text{ Hz} = 1 \text{ s}^{-1}$.

Friedmann equation An equation, arising in the context of the Friedmann–Robertson–Walker models, that relates the value of the scale factor $R(t)$ and its rate of change $\dot{R}(t)$ to the curvature parameter k , the cosmic density ρ and the cosmological constant Λ . Given the value of the parameters k , ρ and Λ , the process of ‘solving’ the Friedmann equation leads to an expression for R as a function of the time t that may be presented as a graph of R against t . Such an expression (or graph) substantially determines the evolution of the cosmological model.

Friedmann–Robertson–Walker models A class of cosmological models based on general relativity and the assumption that the Universe is homogeneous and isotropic (i.e. the cosmological principle). The geometric properties of space–time in these models are described by the Robertson–Walker metric which includes a curvature parameter k , and a scale factor $R(t)$ that satisfies the Friedmann equation.

FRW models A common abbreviation of Friedmann–Robertson–Walker models.

Galactic coordinates A coordinate system on the sky, whose two elements are Galactic longitude l , and Galactic latitude b , resembling longitude and latitude on the Earth. The orientation of the coordinate system is defined to make it useful for describing the locations of objects in the Galaxy from the viewpoint of the Sun. The Galactic equator is chosen to coincide more-or-less with the Galactic plane, the direction $(l, b) = (0^\circ, 0^\circ)$ is roughly in the direction of the Galactic centre, $(l, b) = (90^\circ, 0^\circ)$ is roughly in the direction of motion of the Sun around the Galactic centre, and $b = 90^\circ$ is the direction in the sky perpendicular to the disc, that lies above the northern hemisphere of the Earth.

Galactic disc A major structural component of the Galaxy, containing most of the visible matter, which lies in a highly flattened distribution. The Sun is located in the disc.

Galactic equator The directions in the sky, close to the Galactic plane, whose Galactic latitude is $b = 0^\circ$. *See* Galactic coordinates.

Galactic fountain A flow of hot gas away from the disc of the Galaxy due to heating by supernova explosions. The gas is believed to cool and then be attracted back to the disc by gravity.

Galactic latitude The Galactic coordinate, denoted b , that measures the angular position of an object relative to the plane marked out by the Galactic equator, which is similar to its angular position relative to the Galactic plane.

Galactic longitude The Galactic coordinate, denoted l , that measures the angular distance of an object around the Galactic equator, from a reference point $l = 0^\circ$ roughly in the direction of the Galactic centre.

Galactic plane The plane defined by the distribution of stars in the flattened disc of the Galaxy, with equal amounts of material on either side. The Sun is located close to, but not exactly in the plane. It may be distinguished from the Galactic equator, which is the plane of a coordinate system defined for convenience to pass through the Sun, tied only approximately to the true distribution of matter in the disc.

Galactic spheroid A structural component of the Milky Way, with the shape of a spheroid, consisting of the halo and nuclear bulge. It extends several tens of kiloparsecs from the Galactic centre. The disc lies within the spheroid, but is not considered to be part of the spheroid.

galaxies Collections of luminous stars, non-luminous dark matter, and in the case of spiral and irregular galaxies some amount of gas and dust, that are gravitationally bound to one another and separated from other similar structures usually by distances of tens of kiloparsecs or more. Various categories of galaxies may be defined based on their appearance, such as spiral galaxies (barred or normal), elliptical galaxies, lenticular galaxies and irregular galaxies.

gaseous corona The body of very hot tenuous gas in the halo of a spiral galaxy.

general relativity A theory of gravity, proposed by Albert Einstein in 1916, according to which gravitational phenomena are a consequence of the geometric distortion of space and time (described mathematically by the curvature of space–time). Formally, the theory is based on the Einstein field equations, but it is often summarized by the somewhat overly simple statement ‘matter tells space how to curve; space tells matter how to move’.

geometrical methods (of distance measurement) Any method of distance measurement based on measuring the angular diameter of a feature of known linear diameter. In practice, geometrical methods of distance measurement are not commonly used because there are few astronomical bodies with known linear diameters.

geometry The branch of mathematics concerned with the study of points, lines, surfaces and volumes in space or space–time and the relationships between them.

globular clusters Clusters of 10^5 to 10^6 very old stars tightly bound by gravity into a spherical region of space less than about 50 pc in diameter. The 150 or so globular clusters associated with the Milky Way are found in a spherical distribution about the centre of our Galaxy. Similar distributions are seen in other galaxies.

grand unified theory (GUT) A physical theory which, it is supposed, should describe the strong, weak and electromagnetic interactions as different manifestations of a single type of interaction. Several candidate grand unified theories exist, but all are speculative and difficult to test experimentally.

gravitational instability The process by which a region of enhanced density becomes more pronounced as a result of its own enhanced gravitational attraction.

gravitational lens An object that, by virtue of its gravitational field, forms an image (or images) of a background source of electromagnetic radiation.

gravitational microlensing The term used to describe gravitational lensing effects that are produced by relatively low mass objects such as stellar remnants, brown dwarfs or planets.

gravitationally bound (system) A system of bodies whose gravitational field and distribution of velocities is such that members of the system cannot escape from the system (except by the relatively slow process of evaporation).

group A collection of galaxies that contains fewer than about 50 members. They are believed to be gravitationally bound systems.

Gunn–Peterson effect The effect, expected to be seen in the spectra of sufficiently distant quasars, whereby electromagnetic radiation at wavelengths shorter than the Lyman α line (121 nm) should be absorbed by smoothly distributed neutral hydrogen in the intergalactic medium. This effect has not been unambiguously observed and is certainly not seen in the spectra of quasars with redshifts up to about 5, indicating that the reionization of the intergalactic medium occurred when the Universe was less than about 10% of its present age.

hadron An elementary particle that consists of a cluster of three quarks (or three antiquarks) or of a quark–antiquark pair.

halo A major component of spiral galaxies, spheroidal in shape, and extending several tens of kiloparsecs from the centre of the galaxy. The disc lies within the halo, but is not considered part of the halo. The halo contains mainly Population II stars, with some tenuous gas (see gaseous corona). The halo is sometimes referred to as the ‘stellar halo’ in order to distinguish it from the dark matter halo.

Heisenberg’s uncertainty principle A fundamental principle of quantum physics which, in one form, states that it is not possible to determine to an arbitrarily high precision both the energy of a system and the time at which the measurement is made. Mathematically, the relationship between the uncertainties in the energy of the system (ΔE) and in the time of measurement (Δt) can be expressed as $(\Delta E \times \Delta t) > h/2\pi$ (where h is the Planck constant).

Hertzsprung–Russell diagram A diagram showing the luminosity and temperature of stars, which is useful for comparing large numbers of stars and for tracking their evolution. Photospheric temperature is shown along the horizontal axis (increasing to the left), and luminosity is shown along the vertical axis. A star appears as a point on the diagram, corresponding to its observed temperature and luminosity.

hierarchical scenario A proposed process for the formation of structure in the Universe which proceeds by the merging of relatively low-mass structures to form more massive structures. It is also referred to as the bottom-up scenario.

high-velocity clouds Clouds of atomic hydrogen well away from the Galactic disc, that are moving rapidly relative to the Sun. Their distances are almost impossible to judge, and there is uncertainty whether they are located within or beyond the Galactic halo.

high-velocity stars Stars, typical of Population II but seen as their orbits carry them through the Galactic disc, whose velocities consequently are abnormally high relative to the disc stars that surround them.

HII regions Hot, luminous region of the interstellar medium, comprising ionized hydrogen gas that is made visible by the presence of a hot, young star or stars. Strong ultraviolet radiation from hot stars ionizes the hydrogen, and the occasional recombination of an electron and proton to form a neutral hydrogen atom results in the emission of light, before the hydrogen is reionized.

homogeneous A term meaning ‘the same everywhere’.

horizon distance At any instant in the history of the Universe, the maximum distance that a physical signal could have travelled in the time that had elapsed up to that instant.

horizon mass The mass contained within a sphere with a radius equal to the horizon distance.

horizontal branch A region on the Hertzsprung–Russell diagram occupied by stars of low mass and low metallicity after they have left the red giant branch during helium core burning. It is often seen in H–R diagrams of globular clusters, where many stars have similar luminosity, but a wide range of surface temperatures and hence lie in an approximately horizontal strip.

host galaxy (of an AGN) The galaxy in which an AGN is found.

hot big bang A theory of cosmic evolution, according to which the current state of the Universe results from the expansion and cooling of a hot, dense and highly uniform initial state.

hot dark matter (HDM) Dark matter which is comprised of particles that are moving at speeds close to the speed of light.

H–R diagram *See* Hertzsprung–Russell diagram.

Hubble classes The four major classes of galaxy: elliptical (E), irregular (Irr), lenticular (S0) and spiral (S). The lenticular and spiral galaxies can be further classified as barred or non-barred.

Hubble classification scheme A classification scheme for galaxies based on their observed shape and structure. *See* Hubble classes; Hubble types.

Hubble constant *See* Hubble’s law.

Hubble diagram A plot of redshift against distance for a sample of distant objects such as galaxies or clusters of galaxies. Such a plot may employ linear or logarithmic axes; if linear axes are used, then the gradient (i.e. slope) of the straight line drawn through the plotted data should equal the Hubble constant divided by the speed of light in a vacuum.

Hubble flow A term used to describe the smooth overall expansion of the Universe that is described by Hubble’s law. Distant galaxies provide observable tracers of this expansion, but only imperfectly since each individual galaxy will have its own ‘peculiar motion’ relative to the Hubble flow.

Hubble parameter The time-dependent quantity $H(t) = \dot{R}(t)/R(t)$ that arises in any Friedmann–Robertson–Walker model in which the scale factor at time t is $R(t)$ and the rate of change of the scale factor at that time is $\dot{R}(t)$. To the extent that such a model represents the real Universe, the current value of the Hubble parameter, $H(t_0)$, should equal the observed Hubble constant H_0 .

Hubble time The time $t = 1/H_0$, where H_0 is the Hubble constant, that provides a useful reference value in discussions of cosmic age.

Hubble types The subdivisions of the Hubble classes in the Hubble classification scheme for galaxies. The galaxies belonging to the elliptical class may be typed as E0, E1, E2 ... E7, according to their observed shape. Spiral (and barred spiral) galaxies can be typed as Sa, Sb, Sc (and SBa, SBb, SBc), according to the openness of the spiral arms and the size of the galactic nucleus relative to the disc of the galaxy.

Hubble's law The observationally based law, discovered by Edwin Hubble, according to which the distance (d) and redshift (z) of (moderately) distant galaxies are approximately related by

$$z = \frac{H_0}{c} d$$

where H_0 is the Hubble constant and c is the speed of light in a vacuum.

ICM *See* intracluster medium.

inflation An episode of rapid and accelerating expansion in the early Universe. Such a process would have occurred if the effective value of the cosmological constant temporarily became very large. It is speculated that this may have happened immediately before the end of grand unification, as a result of the development of a 'false vacuum' with a high density of vacuum energy. However, there is no accepted theoretical explanation of why such conditions might have occurred. Despite the lack of a mechanism for inflation, it is an attractive hypothesis because it provides a natural solution to the horizon and flatness problems, as well as offering an explanation of the origin of cosmic structure.

initial singularity The state, in some cosmological models, in which some physical quantities (such as density) have implied values that are infinite at the time $t = 0$.

instability strip A roughly vertical region on the Hertzsprung–Russell diagram where the structure of stars is unstable. Any star in this region pulsates and therefore shows variability. Amongst the stars found in this region are classical Cepheids and RR Lyrae variables.

integrated spectrum The overall spectrum of electromagnetic radiation from an entire galaxy, or from a large region of a galaxy, made up from the spectra of stars and other luminous matter.

interacting galaxies Two (or more) galaxies, interacting with each other in a manner that wreaks profound internal changes in both.

interaction energy The typical amount of energy available in a particle interaction. In a system that is in thermal equilibrium at a temperature T , the interaction energy has a value of approximately kT (where k is the Boltzmann constant).

intercloud medium A component of the interstellar medium characterized by very low density, within which the other components of the interstellar medium, such as dense clouds and HII regions, are embedded.

Intermediate Population The name given to stars having ages, metallicities and motions intermediate between those of Population I and Population II stars. It is synonymous with the thick disc.

interstellar medium (ISM) The matter that thinly fills interstellar space in the Galaxy. It consists of gas (mainly hydrogen), with a trace of dust, and occurs as many, highly varied types of region, such as dense clouds, HII regions and the intercloud medium.

intracluster medium (ICM) The gas that lies between the galaxies within a cluster of galaxies. Typically such gas is very hot and ionized, and has a very low density.

ionized hydrogen Hydrogen in a state where the single proton and single electron that form atomic hydrogen have acquired sufficient energy (13.6 eV or more) that they are no longer bound to one another. The energy may come from collisions with other fast-moving particles, or from electromagnetic radiation of sufficiently high energy/short wavelength.

irregular (galaxy) Any member of the Hubble class of galaxies characterized by having no overall symmetry or regularity. Membership of this class is denoted by the symbol Irr.

ISM *See* interstellar medium.

isochrone A curve in the Hertzsprung–Russell diagram showing the theoretically expected locations of stars of different masses, temperatures and luminosities but the same age (and the same initial metallicity).

isophote A curve linking points of equal apparent surface brightness.

isotropic A term meaning ‘the same in all directions’.

Jeans mass The minimum mass that a uniform, spherical, non-rotating cloud must have if it is to collapse under its own gravitation. In the context of evolutionary cosmology, the Jeans mass at any time (based on the mean cosmic density and temperature at that time) determines which of two evolutionary pathways an over-dense region will follow. A region that exceeds the Jeans mass will contract under the influence of gravity. A region that has a mass lower than the Jeans mass will be supported by its internal pressure and will be stable against gravitational collapse.

Keplerian orbit An orbit arising when the mass of a gravitating system is dominated by a single body. This applies in the case of the Solar System where the Sun dominates, but not in the case of the disc of a galaxy where large fractions of the mass lie away from the centre.

kiloparsec A unit of distance, equal to one thousand parsecs and usually denoted 1 kpc, that is convenient for measuring distances on the scale of a galaxy.
 $1 \text{ kpc} = 1000 \text{ pc} = 3.09 \times 10^{19} \text{ m}$.

λF_{λ} (lambda-eff-lambda) The product of multiplying the spectral flux density F_{λ} at a wavelength λ by that wavelength. When plotted against wavelength (to form a spectral energy distribution) this quantity provides a measure of the contribution to the total luminosity of a source that arises from different parts of the electromagnetic spectrum.

large-scale structure A generic term for the distribution of matter in the Universe on or exceeding the scales of superclusters, i.e. on linear scales exceeding tens of megaparsecs.

last-scattering surface The surface defined by the locations at which photons in the cosmic microwave background last underwent significant interaction with matter (with the exception of gravitational effects). This interaction was due primarily to electron scattering, and so last-scattering occurred at about the time of recombination.

Lemaître model A cosmological model, belonging to the class of Friedmann–Robertson–Walker models, which starts with a big bang and which expands perpetually, but in such a way that there is a ‘coasting’ or ‘pseudo-static’ phase at intermediate times during which the rate of change of the scale factor approaches zero so that the model behaves like the Einstein model. The Lemaître model is characterized by a positive cosmological constant ($\Lambda > 4\pi G\rho/c^2$) and a positive curvature parameter ($k = +1$).

lenticular (galaxy) Any member of the Hubble class of galaxies characterized by having a disc but no spiral arms, possibly related to spiral galaxies. Membership of this class is denoted by the symbol S0, or SB0 in the case of a barred lenticular galaxy.

lepton One of a family of six elementary particles that includes the electron and the three types of neutrino.

lepton number A quantity that is conserved in all particle interactions (with the exception of some speculative interactions predicted by grand unified theories). The lepton number of any lepton is +1 and that of any antilepton is −1 respectively. The lepton number of any other particle is zero.

light curve A diagram showing the variation of brightness (e.g. magnitude, flux density or luminosity) with time, for a celestial object such as a variable star or supernova.

light-year The distance travelled by light (or any other form of electromagnetic radiation) through a vacuum in one (tropical) year. $1 \text{ ly} \approx 9.46 \times 10^{15} \text{ m}$.

Local Group A sparse cluster of over 30 galaxies within about 1 Mpc of the Milky Way, and including the Milky Way.

Local Supercluster The supercluster of clusters of galaxies to which the Local Group belongs. It is 25–50 Mpc across, and contains 1000 or so bright galaxies.

luminosity A quantity describing the rate at which energy is carried away from a luminous object by electromagnetic radiation. The SI unit of luminosity is the watt (W), where $1 \text{ W} = 1 \text{ J s}^{-1}$.

Lyman α (line) The spectral line that arises from the electronic transitions in the hydrogen atom from $n = 1$ to $n = 2$ (absorption) or from $n = 2$ to $n = 1$ (emission).

Lyman α forest A set of absorption lines (which are predominantly due to Lyman α absorption) appearing in the spectrum of a quasar. The absorption lines are due to clouds of neutral intergalactic gas that lie along the line of sight to that quasar.

Lyman series The series of electronic transitions in the hydrogen atom that involve a change to or from the $n = 1$ state.

MACHO (massive astrophysical compact halo object) A hypothetical astronomical body with a moderate mass but a low luminosity (such as a stellar remnant or a body of substellar mass) that might exist undetected in the halo of a galaxy. A large population of such objects might account for a significant amount of (baryonic) dark matter.

main sequence turn-off The point on the main sequence of the Hertzsprung–Russell diagram of a star cluster above which no stars are present. It corresponds to stars that are just reaching the end of their time on the main sequence, and is therefore an indication of the age of the cluster.

mass accretion rate The rate at which material is transferred to an astronomical body.

mass-to-light ratio The value obtained by dividing the mass M of a system by its luminosity L .

mathematical model A mathematical representation of some process or system that captures certain essential features of its subject but does not attempt to recreate every detail. A mathematical model is usually based on one or more equations and many involve one or more parameters that might have to be determined by observation.

merger tree A schematic representation of the history of a galaxy in terms of the merger events that have led to the formation of that galaxy.

metallicity (Z) A numerical measure of the proportion of heavy elements in a sample of material, obtained by dividing the mass of heavy elements (i.e. ‘metals’ to an astronomer) in the sample by the total (baryonic) mass of the sample. In the Sun, $Z \approx 0.02$.

metals To an astronomer, all elements except hydrogen and helium.

Milky Way The name given to the Galaxy of which the Sun is a member. Also the name given to the diffuse band of light seen when an observer on the Earth looks in a direction near the plane of the Galaxy, where uncountable numbers of unresolved stars produce a background glow.

molecular clouds Any cloud-like region in the interstellar medium in which hydrogen is predominantly in the form of molecular hydrogen. Dense clouds are found in this type of region.

molecular hydrogen Hydrogen in a state where many pairs of hydrogen atoms have become bound to one another to form hydrogen molecules (H_2). This is only possible in cold, dense clouds where neither collisions with fast-moving particles, nor ultraviolet radiation is likely to break apart (dissociate) the molecules.

momentum A property of systems (such as arrangements of particles of matter or distributions of radiation) that measures their ability to impart an impulse. According to general relativity, the distribution of momentum throughout a region of space–time is one of the factors that plays a role in determining the curvature of that region of space–time. The SI unit of momentum is the kilogram metre per second ($kg\ m\ s^{-1}$).

monolithic collapse A scenario for galaxy formation in which the gravitational collapse of a single over-dense region gives rise to a single galaxy.

morphology (of a galaxy) The observed shape and large-scale structure of a galaxy, used as the basis of the Hubble classification.

M-theory A speculative physical theory that unifies gravitation with the strong, weak and electromagnetic interactions. One feature of M-theory is that it requires 11 dimensions, rather than the four dimensions of space–time with which we are familiar.

multipole number The numerical quantity, usually denoted l , that is plotted on the horizontal axis of an angular power spectrum, and which indicates an angular scale (on an anisotropy map or elsewhere) of $\theta = 180^\circ/l$.

narrow-line region (NLR) The body of gas responsible for emitting the narrow emission lines in an AGN. The width of narrow emission lines corresponds to radial velocity variations in the range 200 to 900 $km\ s^{-1}$.

neutralino An uncharged elementary particle that is predicted by some supersymmetric extensions to the standard model. The existence of such particles has not been established. The neutralino is a candidate weakly interacting massive particle (WIMP).

neutrino decoupling A process in which changing physical conditions prevent the frequent interaction between neutrinos and other types of elementary particles. The term neutrino decoupling is often used to refer to the postulated episode in cosmic history in which the declining density and temperature of matter caused cosmic neutrinos to cease their frequent interactions with every other kind of particle (except for the effects of gravity). Neutrino decoupling is believed to have occurred when the age of the Universe was about 0.7 s.

non-baryonic dark matter A component of dark matter which can be shown not to be made of baryons.

normal galaxy A galaxy which has an approximately constant luminosity that can largely be accounted for in terms of the stars and gas that the galaxy contains.

number density The quantity used to describe the number per unit volume of particles or bodies of some specified type (e.g. electrons or stars). The SI unit of number density is the per cubic metre (m^{-3}).

OB association A group of young stars containing several stars of spectral types O and B.

oblate spheroid An ellipsoid having the shape of a flattened sphere, i.e. with two principal axes of equal length and a shorter third axis.

observational cosmology The branch of science concerned with measuring the parameters that characterize the Universe. These parameters include the Hubble constant, the current value of the deceleration parameter and the current values of the density parameter for matter and the density parameter for the cosmological constant.

open cluster A cluster of up to a few hundred stars, formed from a cloudlet that has fragmented from a larger dense cloud. The stars are only loosely bound together by gravity, hence the name ‘open’, in contrast to the much stronger binding of stars in a globular cluster.

open model A cosmological model, belonging to the class of Friedman–Robertson–Walker models, that starts with a big bang and expands continuously without limit, so the rate of change of the scale factor is always positive (i.e. $\dot{R} > 0$ at all times). The open model is characterized by a zero cosmological constant ($\Lambda = 0$) and a negative curvature parameter ($k = -1$). In such a model the cosmic density is always less than the critical density.

optically violent variables (OVV) A subclass of blazar. In contrast to BL Lac objects, some broad emission lines are often observed in the spectra of OVVs.

Orion–Cygnus Arm See Orion Spur.

Orion Spur Also called the Orion–Cygnus arm. A strip-shaped region of the Galaxy near the Sun occupied by astronomically young objects, either a spur of a spiral arm, or an arm in its own right. The Sun is located in the Orion Spur.

pair-creation The physical process in which, given sufficient energy, a particle and its antiparticle can spontaneously form. This is the opposite process to annihilation.

parallax The quantity that describes the change in direction to a celestial body (relative to a background of far more distant bodies) resulting from a given change in position of the observer perpendicular to the direction of the body. The term parallax is often used to refer specifically to stellar parallax, p , where the change in position of the observer is one astronomical unit. This quantity is important in the determination of the distance of nearby stars.

parsec The distance to a celestial body that has a parallax of one arc second. $1 \text{ pc} \approx 3.26 \text{ light-years} \approx 3.09 \times 10^{16} \text{ m}$.

peculiar galaxy A galaxy of more-or-less readily apparent Hubble type, but with some abnormal feature (such as a jet); denoted by ‘p’ after the Hubble type.

peculiar motion (of a galaxy) The component of motion of a galaxy as a whole that is additional to that arising from its participation in the Hubble flow.

period–luminosity relationship A correlation between period and luminosity; in particular the relationship between period and luminosity of Cepheid variables that enables these stars to be used as standard candles. (Absolute visual magnitude, M_v , is generally used in place of luminosity when displaying this relationship.)

Perseus Arm A strip-shaped region of the Galaxy, slightly further from the Galactic centre than the Sun, occupied by astronomically young objects. It is one of the local spiral arms of the Galaxy.

photodisintegration The process in which a nucleus is split apart by the absorption of a gamma-ray photon. This type of reaction plays an important role in the later stages of stellar nucleosynthesis.

photon The particle of electromagnetic radiation in the photon model of light. The photon energy ε is proportional to the frequency f of the associated radiation; $\varepsilon = hf$ where h is the Planck constant.

photon–baryon fluid The fluid-like system in the early Universe, formed by the incessant interaction of radiation and charged baryons, that is characterized in any sufficiently localized region by a specific temperature and pressure. The photon–baryon fluid is subject to the gravitational influence of the dark matter that is also present in the early Universe.

photon energy distribution function A quantity that describes the relative numbers of photons at different energies. Specifically, at some specified energy, the photon energy distribution function is the proportion of photons whose energies lie in a narrow energy range around that energy.

Planck era The period in the history of the Universe prior to the Planck time.

Planck time A time determined by a combination of physical constants ($(\hbar G/2\pi c^5)^{1/2} = 5.38 \times 10^{-44}$) that represents the earliest time in cosmic history at which currently established physical theory might be used to study the nature and evolution of the Universe. Prior to the Planck time, gravity might have played a significant role in particle interactions.

Population I Stars found in the discs of spiral galaxies, generally less than 10^{10} yr old, and have a metallicity similar to that of the Sun ($Z \sim 0.01$ to 0.04).

Population II Stars found in the Galactic spheroid of spiral galaxies and in elliptical galaxies, generally more than 10^{10} yr old. Population II stars in the halo have metallicities $Z < 0.002$, but Population II stars in the bulge have metallicities similar to Population I stars ($Z \sim 0.01$ to 0.04).

population synthesis A method of investigating the stellar content of galaxies, in which the relative abundance of various types of star is assumed, and their integrated spectrum calculated and compared with that observed from the galaxy in question. On the basis of this comparison, the relative abundances of different stellar types are modified until the best fit between the model and actual spectrum is determined.

precision cosmology A term used to describe recent developments in cosmology whereby the values of a range of key cosmological parameters have been determined with high precision (and possibly good accuracy).

primordial nucleosynthesis The nuclear processes that were responsible for the initial formation of the nuclei of light elements (such as helium and lithium) in the early Universe. It is generally believed that primordial nucleosynthesis began when the age of the Universe was about 3 minutes, and that it continued for about thirty minutes.

prolate spheroid An ellipsoid with the shape of an elongated sphere, i.e. with two principal axes of equal length and a longer third axis.

Pythagoras's theorem A theorem of geometry according to which the square of the length of the longest side of a right-angled triangle is equal to the sum of the squares of the lengths of the other two sides ($c^2 = a^2 + b^2$).

quantum fluctuations Variations in energy density of the vacuum that occur on a microscopic scale due to the presence of virtual particles.

quantum theory A wide-ranging theory that describes, amongst other things, the structure and behaviour of atoms and their interaction with electromagnetic radiation. It accounts for the phenomena that are embraced by the photon model of light, and implies the existence of energy levels in atoms.

quark–hadron phase transition A process in which changing conditions cause a ‘gas’ of free quarks and antiquarks to transform itself into a gas of hadrons and antihadrons. The term is also used to describe the episode in cosmic history in which this process is believed to have affected the baryonic matter in the Universe. It is believed that the quark–hadron phase transition occurred when the age of the Universe was about 10^{-5} s.

quasar/QSO A kind of active galaxy, typically characterized by a point-like appearance and a very large redshift. Quasars provide very distant and very bright examples of the effect of an AGN in a galaxy where the rest of the galaxy is so faint that it can only be discerned with difficulty, if at all.

quintessence A hypothetical and exotic form of matter, probably better thought of as a field filling the Universe, that would exert a negative pressure. The energy associated with this kind of matter (or field) would constitute the dark energy. In contrast to some of the other proposed explanations of dark energy, the energy density of quintessence might vary with time and spatial position.

radiation-dominated era The period of the history of the Universe when the energy density of radiation exceeded that of matter.

radiation pressure A pressure exerted by photons on any object that absorbs or scatters them.

radio galaxy A kind of active elliptical galaxy which shows (usually) two regions of diffuse radio emission from either side of the galaxy – radio lobes. An AGN is needed to power the radio lobes, and can be seen in the centre of the parent galaxy.

random uncertainties Uncertainties in the measured value of a quantity that cause repeated measurements of that quantity to vary about some mean value.

recombination A process in which an electron and an ion combine, i.e. the opposite of ionization. The electron is typically captured into a high-energy orbit and then cascades downward through the atom's energy levels emitting photons as it does so. The term recombination is also used to refer to the postulated episode in cosmic history in which the baryonic matter of the Universe made the transition from being predominantly plasma to predominantly neutral atoms. Recombination is believed to have occurred when the age of the Universe was between about 3 and 4×10^5 years.

redshift The numerical quantity used to measure the shift in wavelength of a spectral line. If a spectral line is emitted at a wavelength λ_{em} and observed at a wavelength λ_{obs} , the redshift is defined by

$$z = \frac{\lambda_{\text{obs}} - \lambda_{\text{em}}}{\lambda_{\text{em}}}$$

reionization A process in which a formerly ionized medium that had undergone recombination to become neutral is again ionized. The term reionization is often used to refer to the postulated episode in cosmic history in which much of the neutral hydrogen became ionized, perhaps due to an increase in the intensity ultraviolet light from hot stars or from AGN. Reionization is believed to have occurred when the age of the Universe was less than 10% of its current value.

relative density fluctuation The numerical quantity used to describe the extent to which the density of a given region of the Universe departs from the mean density of the Universe by expressing the difference between the density of the region and the mean density as a fraction of the mean density.

retrograde Motion around the Galaxy in the opposite direction to that of disc stars.

richness A quantity used in the classification of clusters of galaxies that describes the number of galaxies (above a certain threshold luminosity) present within a cluster. Rich clusters contain relatively high numbers of galaxies.

rigid body rotation A pattern of rotation in which all parts of the rotating system have the same period of rotation, irrespective of their distance from the centre of rotation. This is the kind of rotation exhibited by a solid planet and should be contrasted with the differential rotation that characterizes objects such as the Sun and the Milky Way.

Robertson–Walker metric An expression, applying to any space–time that is homogenous and isotropic, that relates the physical separation ds of two narrowly separated events to the coordinate differences (typically dx , dy , dz and dt) that may be used to describe the relative locations of those events. The Robertson–Walker metric involves a curvature parameter k and a scale factor $R(t)$ that respectively characterize the curvature of space and its expansion (or contraction) with time.

rotation curve A plot of rotation speed against radial distance for a rotating system.

RR Lyrae stars A type of regular variable star. RR Lyrae stars are found on the horizontal branch of the H–R diagram, and within the instability strip and hence their envelopes pulsate. Pulsation periods are around 12 hours. As all horizontal branch stars have very similar absolute magnitudes, RR Lyraes are good standard candles for measuring distances within the Galaxy. They are Population II stars.

Sachs–Wolfe effect The dominant source of angular power in the angular power spectrum of the cosmic microwave background for multipole numbers of 50 or less (i.e. on angular scales of a few degrees or more). The effect is largely due to the gravitational redshift of radiation coming from the denser parts of the last-scattering surface.

Sagittarius A* A very compact, strong radio source that lies at the very centre of the Galaxy. The motions of stars around Sgr A* suggest it is a black hole with a mass about 2.6×10^6 greater than the mass of the Sun.

Sagittarius–Carina arm A strip-shaped region of the Galaxy, slightly closer to the Galactic centre than the Sun, occupied by astronomically young objects. It is one of the local spiral arms of the Galaxy.

Sagittarius dwarf galaxy A dwarf galaxy (discovered in 1995) that is in the process of merging with the Milky Way.

scale factor A time-dependent quantity, usually denoted $R(t)$, that appears in the Robertson–Walker metric where it describes the expansion or contraction of space in a homogeneous and isotropic Universe. The scale factor plays a crucial role in relating the coordinates of points to the physical distance between these points. In an expanding Universe, two points that have a fixed co-moving coordinate separation r will be separated by a growing physical distance l that is proportional to $R(t)$, and which may be, for example, $l = R(t) \times r$.

scale height The distance, measured from the Galactic plane, over which the number density of disc stars decreases to 1/e times the density in the Galactic plane. (The value $e \approx 2.718$ is the basis of the exponential function.)

Schwarzschild radius The radial distance from the centre of a black hole at which the escape speed equals the speed of light.

SED See spectral energy distribution.

semimajor axis Half the longest diameter of an ellipse.

semiminor axis Half the shortest diameter of an ellipse.

Seyfert galaxy A kind of active spiral galaxy which has an AGN that appears as a central, point-like source in optical images.

SFR See star formation rate.

Silk damping The dominant source of angular power in the angular power spectrum of the cosmic background radiation for multipole numbers in excess of $l = 1000$ (or angular scales of less than 0.1 degree or so). The effect arises from the suppression of acoustic waves of very short wavelength due to the free movement of photons between encounters with charged particles.

space The aspect of space–time that consists of all the possible positions that a particle might occupy according to some observer. Space is three-dimensional and possesses a range of geometrical properties.

space–time The four-dimensional entity that unites space and time. It consists of all the possible events at which a particle might be present, and is characterized by geometrical properties such as curvature. When making measurements, any observer will divide space–time into space and time, but the way in which that division is made by two different observers will generally be different and depends on the relative motion of those two observers.

spectral energy distribution (SED) A form of the broadband spectrum of an astronomical source that shows the quantity λF_λ against wavelength λ . It shows the relative contributions to the total luminosity that are emitted in different wavelength ranges.

spectral excess The feature in the spectrum of a galaxy that represents the excess of emission in a certain wavelength band over that which would be expected due to emission from stars alone. Spectral excesses in the infrared are characteristics of starburst and active galaxies.

spheroid A three-dimensional shape that may be pictured as a sphere that has been flattened or stretched in one direction. This is the *shape* of both the (stellar) halo and the dark-matter halo of the Galaxy, and it is the *name* given to the region of the Galaxy associated with the halo and sometimes also the bulge.

spiral arms The regions of a spiral galaxy traced out by bright stars, HII regions, and other astronomically young objects. These mark out a fragmented, roughly spiral pattern within the disc of the galaxy, extending outwards from near its centre.

spiral-arm tracers Those young, short-lived astronomical objects associated with recent star formation that map out the spiral arms of a spiral galaxy. They include HII regions, O and B stars, classical Cepheid variable stars, and T Tauri stars.

spiral density wave A long-lived, self-consistent pattern of density enhancement that may arise in a disc of stars and gas, thought possibly to account for the pattern of star formation that gives rise to spiral arms in spiral galaxies.

spiral galaxy Any member of the Hubble class of galaxies characterized by having a disc and spiral arms. Membership of this class is indicated by the letter S, or SB in the case of a barred spiral galaxy.

standard candle Any type of object whose luminosity is directly indicated by its observable properties, thus allowing its distance to be inferred from the difference between its apparent brightness and its true brightness.

standard candle methods Any method of distance determination based on the use of a standard candle, such as a Cepheid variable of known period, or a Type Ia supernova with a known rate of decline in brightness.

standard model (of elementary particles) A theory which describes all known elementary particles and their interactions. No discrepancy between the predictions of the standard model and experimental results has yet been discovered.

star formation rate (SFR) The rate at which stars are forming, usually quoted as the number of solar masses per year, in some specified volume.

starburst galaxy A galaxy in which a recent episode of star formation is believed to have occurred, leading to optical emission lines and infrared radiation being emitted from an extended region of the galaxy.

static A property of certain cosmological models (or more specifically of certain space–times) implying that space is neither expanding nor contracting.

stellar halo A term sometimes used to distinguish the halo from the dark-matter halo. *See* halo.

stellar parallax *See* parallax.

stellar population A grouping of stars characterized by their age, composition and location or motion. *See* Intermediate Population; Population I; Population II.

sublimate The process in which a solid material (e.g. dust) is transformed, on heating, into the gas phase without going through a liquid phase.

sublimation radius The distance from the engine of an AGN at which the temperature is just sufficient to cause dust particles to sublimate.

superbubble A hot, bubble-like region of the interstellar medium where the gas has been heated greatly by large numbers of supernova explosions from stars in that region.

supercluster An association of galaxies of order 25 to 50 Mpc across.

supermassive black hole A black hole with a mass in excess of about $10^7 M_{\odot}$.

supersymmetry A type of symmetry which has been suggested, but not proven, to apply to particle interactions. Supersymmetric theories predict the existence of particles that have not been observed in nature. Some of these particles (such as the neutralino) are of cosmological significance because they are candidates for WIMPs.

surface brightness profile A plot of the apparent surface brightness of a galaxy as a function of radial distance from its centre.

systematic uncertainties Uncertainties in the measured value of a quantity that cause repeated measurements of that quantity to always differ from the true value in the same way.

T Tauri stars Newly formed, low-mass, star-like bodies that have not yet reached the main sequence.

temperature fluctuation Variations in average temperature, on a given size or angular scale, within a temperature distribution, such as that of the cosmic microwave background.

thermal bremsstrahlung A process by which X-rays are generated in a plasma. Electrons pass close to ions, but without being captured. In doing so their paths are deflected and X-ray photons are emitted.

thermal equilibrium A state in which there is a high level of interaction between matter and radiation which leads to the radiation having a black-body spectrum with a characteristic temperature that is the same as that of the matter.

thick disc A component of the disc of the Galaxy, a few times thicker than the thin disc – the scale height of the thick disc is around 1000 parsecs – and containing fewer stars. Thick-disc stars belong to the Intermediate Population.

thin disc The main component of the disc of the Galaxy, with a scale height around 300 parsecs. Thin-disc stars belong to Population I.

time The aspect of space–time that consists of all the possible instants at which a particle might exist according to some observer. Time is one-dimensional.

top-down scenario A proposed process for the formation of structure in the Universe which proceeds by the fragmentation of relatively high-mass structures to form less massive structures.

triaxial ellipsoid An ellipsoid with three unequal principal axes.

Tully–Fisher relation The relationship between the luminosity of a spiral galaxy and the width of its 21 cm hydrogen emission line. This relation is used to determine the luminosities and hence distances of spiral galaxies.

Type Ia supernovae A class of supernova, used as a standard candle.

unbarred galaxy *See* barred (spiral) galaxy.

unbounded A property of certain cosmological models (or more specifically of certain space–times) implying that any ‘straight’ line may be extended infinitely without ever encountering any boundary or edge. Note, however, that in an unbounded space–time there is no guarantee that a straight line may not close back upon itself, as shown by the finite but unbounded space of the Einstein model.

vacuum energy The energy possessed by a region of space that contains no radiation or real particles. This energy is not zero because of the existence of virtual particle–antiparticle pairs, which are continuously being created and annihilated in the vacuum. Vacuum energy provides a possible explanation of the nature of dark energy, though attempts to provide a quantitative basis for such an explanation have so far been unsuccessful.

velocity dispersion A quantity that describes the range of velocities found within a collection of moving objects (*see* virial theorem). The SI unit of velocity dispersion is the metre per second (m s^{-1}).

virial theorem A theorem relating the total kinetic energy to the total gravitational potential energy for a system of gravitationally interacting particles that has settled into a state of equilibrium. A statistical treatment of such systems, leads to the result that the kinetic energy of the system is equal to $-1/2$ times the gravitational potential energy of the system. A consequence of this is that the velocity dispersion of the components of the system is expected to depend on the size of the region they occupy and on their total mass. This result is used to determine the masses of elliptical galaxies and of clusters of galaxies.

virialized The equilibrium state of a gravitationally bound system. The virial theorem applies only to systems in this state.

virtual particles Particle–antiparticle pairs that have a fleeting existence in the vacuum. The rest energy required for particle–antiparticle pair creation is related to the lifetime of the pair by the Heisenberg uncertainty relation.

voids Large (~ 60 Mpc) regions of the Universe in which the number density of galaxies is very low.

weakly interacting massive particle *See* WIMP.

WIMP (weakly interacting massive particle) A hypothetical elementary particle that has a relatively high mass and which only interacts by the weak interaction and gravity. A large population of such particles might account for a significant amount of (non-baryonic) dark matter.

winding dilemma The observation that if a galaxy’s spiral arms consisted of an unchanging population of stars then differential rotation would cause the arms to smear out within a time that is short compared with the age of that galaxy.

zone of avoidance A zone on the sky, close to the Galactic plane, where dust in the interstellar medium obscures our view of more distant objects.

zone of obscuration *See* zone of avoidance.